Photonic Network Communications
https://doi.org/10.1007/s11107-017-0756-2

ORIGINAL PAPER

A novel proposal for all-optical Galois field adder based on photonic crystals

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Received: 14 October 2017 / Accepted: 29 December 2017
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Abstract
In this paper we are going to propose an all-optical structure for implementing Galois field adder. To do so, we will use four optical XOR gates. The working principle of the proposed structure is based on destructive interference of optical waves. By choosing different lengths for the input waveguides, 180° of phase difference will be generated between the optical waves. In the final structure, the normalized power for logic 0 and 1 at the output ports was 1 and 45%. Time delay of the proposed structure is about 1.5 ps.

Keywords Galois field · Adder · Photonic crystal · Logic gates

1 Introduction

Considering the ever-increasing demand for high-speed and high-bandwidth communication systems, it is inevitable to use optical communication systems and networks instead of electronic-based networks and systems. Optical fibers [1–4], filters [5–16], demultiplexers [17–27] and analog to digital converters [28–33] are the main devices used in all-optical communication networks.

In order to make optimum use of optical networks advantages, we should avoid electrical to optical and vice versa conversions; therefore, all of the required data processing should be done in optical domain, which in turn requires optical devices such as optical logic gates [34–40], decoders [41–44], encoders [45–48], adders [49–51].

It has been shown that photonic crystals are promising structures for designing all of the aforementioned optical structures, with suitable dimensions for all-optical integrated circuits. Recently, a wide variety of optical logic devices required in all-optical data processing have been proposed. By using two nonlinear ring resonators inside photonic crystal structures, Andalib et al. [52] proposed an all-optical AND gate. Shaik and Rangaswamy [53,54] used T-shaped waveguides and multi-mode interference effect inside photonic crystals to design different kinds of logic gates such as AND, XOR, XNOR, OR and NOR. Mohebbi et al. [55] used nonlinear defects inside PhC-based optical waveguides to propose all-optical XOR, XNOR, NAND and NOT gates. Alipour-Banaei et al [56,57] proposed NAND and NOR gates using nonlinear resonant rings. A threes-input logic NOR gate was proposed by combining three nonlinear PhC ring resonators with PhC-based waveguides [58].

Optical decoders and encoders are other optical devices required in optical logic circuits and applications. Serajmohammadi et al. [59] proposed a 1–2 PhC-based optical decoder for the first time. They used a nonlinear resonant ring along with bias and control ports for controlling the digital status of two output ports. They extended their work and proposed a 2–4 optical decoder using three nonlinear resonant rings [60]. In recent years, different structures were proposed for realizing optical decoders based on PhCs [44,61]. For realizing a PhC-based encoder, Mehdizadeh et al. [48] combined two optical OR gates with an optical buffer. All of the fundamental gates used in designing the proposed encoder were designed without using nonlinear effect. Also Hassangholizadeh-Kashtiban et al. [46] proposed a reversible optical encoder by using four optical waveguides and two nonlinear elliptical ring resonators.

Liu et al. [49] combined AND and XOR logic gates for realizing an all-optical PhC-based half-adder. Another optical half-adder was proposed by Ghadradan and Mansouri-Birjandi [62] by combining AND and XOR gates. Jiang et al. [51] used self-collimation effect inside 2D PhCs and

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Published online: 15 January 2018

proposed a PhC-based half-adder. Another self-collimation effect-based optical adder was proposed by Xavier et al. [63]. Alipour-Banaei and Seif-Darghahi [64] proposed a full adder by cascading two optical half-adder structures in the proposed structure the delay time was about 6 ps.

In this paper, we aim to design and present a completely new optical logic gate named Galois field adder which has not been designed using PhCs yet. To do so, we will use the optical XOR gate proposed by Karkhanechi et al. [50] as the basic structure and realize the proposed structure using this XOR gate.

The rest of the paper will be organized as follows: in Sect. 2 we briefly introduce the Galois fields; in Sect. 3 we present the design procedure; in Sect. 4 we discuss the simulation results; and finally, in Sect. 5 the conclusion is presented.

2 Galois field

A Galois field (GF) is a mathematical field that contains finite number of elements. GF(2^m) includes all m-bit combinations which can be shown in the form of different powers of a, where a is the primary element of a. Therefore, GF(2^m) has 2^m members, which are as follows:

$$0, 1, a^1, a^2, \ldots., a^{2m-2}.$$

Every Galois field has an m-order primitive polynomial whose root is a. In standard basis for showing Galois fields, any of positions of the m-bit vectors shows a power of a such that the rightmost position corresponds to $a0 = ^1$, and the next position corresponds to a^1, finally the leftmost position corresponds to a^{m-1}. Therefore, for GF(2^4) we have:

$$0000 = 0, 0001 = a^0, 0010 = a^1, 0100 = a^2 and 1000 = a^3.$$

The other members of GF will be obtained using the four above-mentioned primitive members. Because a is the root of the primitive polynomial, we have:

$$a^4 + a + 1 = 0;$$

in GF addition and subtraction are equal and done using a XOR gate. We will have:

$$a^4 = -a - 1 = a + 1 = 0011,$$

Some examples of the higher orders of a will be as follows:

$$a^5 = aa^4 = a\,(a+1) = a^2 + a = 0110,$$
$$a^6 = aa^5 = a\left(a^2 + a\right) = a^3 + a^2 = 1100,$$
$$a^7 = aa^6 = a\left(a^3 + a^2\right) = a^4 + a^3 = a^3 + a + 1 = 1011,$$

and so on.

3 Galois field adder

Galois field adder can be realized using XOR gates between corresponding bits of two GF symbols. Therefore, a 4-bit GF adder schematic is shown Fig. 1, which is composed of four XOR gates.

For realizing the proposed structure, we used the optical XOR gate proposed by Karkhanechi et al. [50] The fundamental structure is used for realizing the GF adder. The fundamental PhC structure used for designing the proposed logic devices is 19 × 53 hexagonal lattice of dielectric rods immersed in air. The refractive index and radius of dielectric rods are 3.3 and $0.18 * a$, where $a = 640$ nm is the lattice constant of the PhC. The band structure diagram of the fundamental structure is shown in Fig. 2, which shows that it has one photonic bad gap in TE and one in TM mode. The TM mode band gap is at $0.3 < a/\lambda < 0.5$ which is equal to $1280\text{ nm} < \lambda < 2133\text{ nm}$.

The proposed structure for the 4-bit all-optical GF adder is shown in Fig. 3. As one can see, it is composed of four optical XOR gates. Every XOR gate consists of two input and one output waveguides. At the joining point of input and output waveguides, four point defects were located whose radius is $0.09a$. In the proposed structure X1, X2, X3 and X4 are the input ports corresponding to the fist 4-bit GF symbol. Similarly Y1, Y2, Y3 and Y4 are the input ports

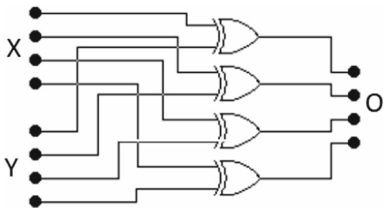

Fig. 1 Schematic of a 4-bit all-optical Galois field adder

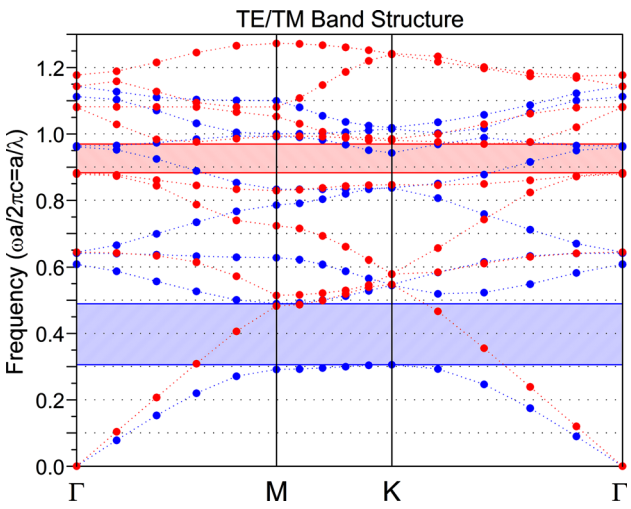

Fig. 2 Band structure diagram of the fundamental PhC

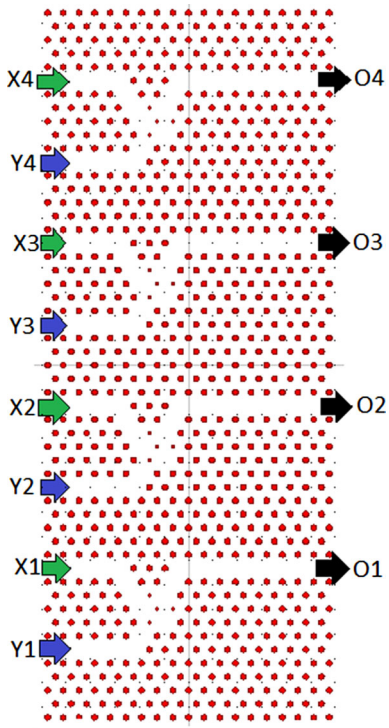

Fig. 3 The proposed all-optical 4-bit Galois field adder

corresponding to the second 4-bit GF symbol. O1, O2, O3 and O4 are the output ports where O4 and O1 are the MSB and LSB of the structure, respectively.

4 Simulation and results

In order to test the functionality of the proposed structure, we are going to simulate the final structure. To do so, we used eight Gaussian optical sources with central wavelength equal to 1550 nm. For each sources ON and OFF states are considered as logic 0 and 1. We suppose that X and Y symbols to be 1100 and 1010. It means that optical sources corresponding to X4, X3, Y4 and Y2 should be ON and the others should be OFF. Figure 4 shows the optical behavior of the proposed structure for the above-mentioned example. In the first stage XOR, because both input ports (X1 and Y1) are OFF, the corresponding output port (O1) will be OFF. In the second stage X2 is OFF and Y2 is ON, and the simulation results show that the optical waves coming from Y2 travels toward O2 and turns it ON. Similarly, in the third stage X3 is ON and Y3 is OFF, and the simulation results show that the optical waves coming from Y2 travels toward O2 and turns it ON. Finally in the fourth stage both input ports (X4 and Y4) are ON, because of different lengths of the input waveguides, and the optical waves in the joint point have phase difference equal to 180°. Therefore, the input waves will have destructive interference and cancel each other and the output power

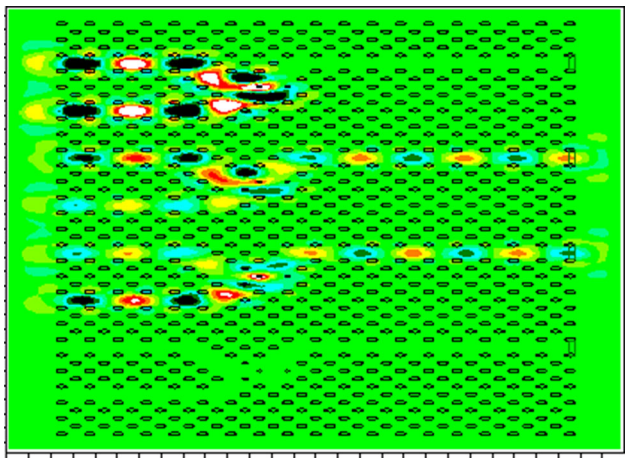

Fig. 4 Optical behavior of the proposed structure

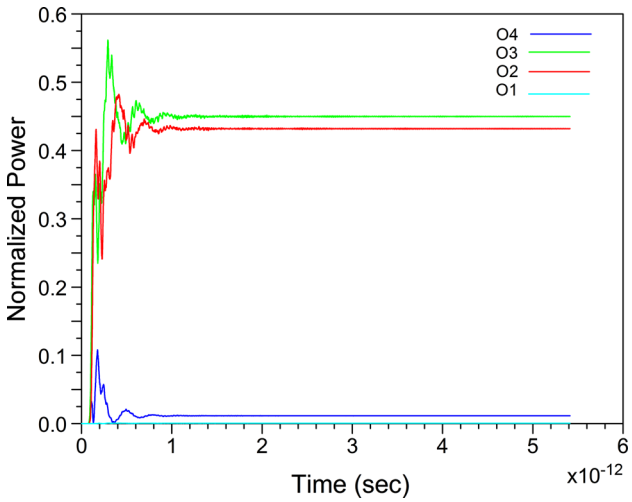

Fig. 5 Time response of the proposed structure

at O4 will be 0. As one can see the produced code at the output ports of the structure is 0110 which is correct according to GF addition rule.

The time response diagram of the proposed structure is shown in Fig. 5, which shows that the normalized power at O4, O3, O2 and O1 is 1, 45, 45 and 0%, respectively. And the time delay is about 1.5 ps.

5 Conclusion

In this paper a novel 4-bit all-optical Galois field adder was proposed and designed by using 2D hexagonal lattice photonic crystals. The proposed structure was realized by combining four optical XOR gates. The simulation results confirmed the functionality of the proposed structure. According to the results obtained from simulations, the normalized power for logic 0 and 1 at the output ports was 1 and 45%. Time delay of the proposed structure is about 1.5 ps.

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